Mechatronic Design of a Hand-Held Instrument with Active Trocar for Laparoscopy

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Abstract— **Instruments used in many types of minimally invasive procedures, in particular laparoscopy, are rigid or only limitedly flexible. Some tasks like suturing are difficult to perform, because they require dexterity when the instruments are limited to four degrees of freedom (DOF). A novel hand-held, lightweight and ergonomic mechatronic instrument is presented in this paper. The instrument has a 4-DOF roll-pitch-roll end-effector controlled using an easy to use handle that provides the surgeon with a 6-DOF movement, including a distal circular movement which resembles the circular movement of stitching. The instrument presented is the result of a global study involving mechanical, electronic and ergonomic aspects, with the aim of developing an instrument that enhances the dexterity of the surgeon while having an intuitive and ergonomic interface.**

INTRODUCTION

Minimally invasive surgery (MIS), compared to open surgery, has advantages specially for patients, but also disadvantages specially for surgeons. In particular, in MIS the patient benefits from the reduced invasiveness, while the surgeons capabilities are limited. In laparoscopy, the insertion point of a rigid instrument inside the abdominal wall limits its movements to only four degrees of freedom (DOF): translation inside the trocar, two angles of inclination of the shaft around the incision point and the rotation angle of the instrument around its longitudinal axis.

In complex and precise tasks such as suturing or knot tying, the limited movements make the performance of the task very difficult. To make a stitch for example, the circular movement required for stitching can only be easily and intuitively performed if the direction of the stitch is at a right angle with respect to the main axis of the instrument. It is clear that instruments with additional DOFs can approach the easiness with which suturing is performed in open surgery. Indeed, robot-assisted laparoscopic suturing has been proved to be faster to learn and perform than manual laparoscopic suturing [1]. In this paper, the mechatronic design of a new instrument with 3 robotic and three manual DOF is presented. The instrument was tested in vitro and in vivo.

State of the art of robotic instruments for laparoscopy

Dexterous instruments for laparoscopy can be put into one of the two following categories:

1) Telesurgery systems have a master console and slave robotic arms. Telesurgery has reached a mature commercial stage and the da Vinci Surgical System [2] is now used in many hospitals. This system solves the problem of dexterity with its 6-DOF instruments. Its intuitive human-machine interface and control mode make hand-eye coordination easier and control of instruments' movements intuitive. Its ergonomic master console provides the surgeon with the comfort of use missing in conventional MIS. But, telesurgery systems prevent direct contact between the surgeon and the patient, have long set up times, take a lot of space in the already crowded operating room and have considerable purchase and maintenance costs.
2) Dexterous hand-held instruments are developed based on the idea of adding more DOF to the conventional instruments. The end-effector of such an instrument is articulated, providing one or more additional DOF. These instruments can themselves be devided into two groups: purely mechanical devices and mechatronic devices. In this section, the state of the art instruments in each of these groups are presented.

Mechanical hand-held instruments: An instrument of this type has an articulated handle, rotating knobs or similar mechanical controllers, and a mechanical transmission system to actuate two or three DOF of the end-effector. They are characterized by clever mechanical design but often have a non-intuitive interface. The controls on the handle need to respect mechanical constraints imposed by the transmission, and thus ease of use is compromised. But they are cheaper and easier to develop and reached the commercial stage quickly after the success of da Vinci showed the advantages of dexterous instruments.

One of the first instruments of this type to be hit the markets is RealHand [3]. It has a wrist added to the end-effector, so that it can yaw and pitch, making the total number of DOF of the instrument six. Its handle is articulated as well to control the additional DOF. When the handle is bent, the end-effector bends in the same direction. The articulation between the handle and the shaft is a universal joint, so that rotating the handle makes the shaft of the instrument rotate. The handle is designed like conventional pistol-grip handles. The cable driven force transmission system reduces the end-effector's rigidity when bent, even when the position of the end-effector is locked. This makes it difficult to keep the orientation of the end-effector while manipulating (unless it is really soft tissues that are manipulated). The bending structure of the wrist is a stack of circular disks and spheres on top of each other driven by six cables. The grasper tip is actuated by pulling/pushing a thin rigid shaft, just as it is

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done in conventional instruments. Autonomy Laparo-Angle [4] has an articulated wrist and an articulated handle. But its end-effector has one more DOF compared to RealHand: the distal tip can turn 360° at any angle using an axial rotation knob in the handle. The handle has a new, more ergonomic design. The transmission mechanism is cable driven and the bending structure is made of a stack of interrelated links driven by 4 cables. The distal rotation of the end-effector is also cable driven and the problem of rigidity persists. Radius [5] has an end-effector that can yaw in only one direction and turn around its axis. The handle is designed like a lever under the middle fingers and its up/down movements correspond to the distal tip's up/down movements. A knob at the end of this lever is used to turn the distal tip. Radius uses a combination of rigid links and gears in its transmission mechanism and effectively solves the problem of rigidity. All three instruments above have 10 mm diameter shafts which makes the size of incisions twice bigger than 5 mm conventional instruments when the main advantage of MIS is the small scars it leaves. Besides, dexterous instruments are mostly envisaged for single incision surgery and having 2 instruments and an endoscope, all in 10 mm diameters in a single incision makes the incision so big that it may cause even more post-operative problems. Roticulator [6] is a 5 mm instrument with a deflectable and turning distal tip. The distal tip is bent by turning an axial knob on the shaft where there is usually a knob for turning the shaft in other instruments. As a result, it is not possible to change the distal tip's deflection during a task. The handle is much like conventional pistol-grip handles. There has also been prototypes of mechanical hand-held instruments developed in research labs that have not been comercialized. [7] mentions some of them in its state of the art section: In [8] an instrument is presented in which the knob that controls the roll angle in conventional tools is replaced by a hinged ring that can be used to steer two DOF of tip deflection. However, a precise movement of the ring needs two or three fingers and it is unclear how the surgeon can simultaneaously open/close the grasper with the scissor-like handle. In [9] a cutter with an alternative handle is presented in which one DOF of tip deflection can be steered by a 2-DOF hinged lever that is also used for opening/closing the gripper. The direction of the cut can therefore be selected freely, at the cost of giving up the knob for adjusting the roll angle, thus leading to a less ergonomic instrument, and of mixing the commands for gripper opening and orienting on the same lever. In [10] the deflection and rotation of the tip are controlled by two separate knobs; in [11] the end-effector has pitch and yaw additional DOF that are controlled by a sphere moved the by the thumb.

Robotic hand-held instruments: To overcome limitations of manual instruments, mechatronic and robotic devices have been developed. In this kind of instruments the manual control and actuation system is replaced with an electronic controller and electrical actuators. These instruments are still at a research stage. In [12] the end-effector can roll-yaw and the opening/closing of the grasper is also motorized. The electric motors are put on the shaft of the instrument. The transmission mecanism is cable driven and a combination of gears makes a distal mechanism that can yaw-roll and at the same time open/close the grasper. The handle has a cylindrical shape and is positioned like a pistol-grip handle in 90° to the shaft. A button and 2 knobs on the handle allow for opening/closing the grasper, deflecting the distal tip or turning it around its axis. The processor unit is away from the instrument and connected to it through an electrical cable. In [13] the driving unit is extended along the shaft. It has 3 motors to actuate the grasper and the two DOF of the distal tip. The end-effector has a multi-slider linkage mechanism, composed of a cascade of 2-DOF joints. The resulting structure can bend in 2 directions (yaw-pitch). But the bending axes are not concurrent. The handle is similar to [12], cylindrical and pistol-grip, with a button and a dial type interface. The processor is integrated in a PC with an electrical cable to the handle. In [7] the motors and controller are all seperated from the instrument. A Bowden cable actuation system with eight pretensioned cables transmits forces of the motors to a pulley box on the instrument's shaft. The end-effector has a Roll-Pitch-Roll kinematics. The control mode is chosen based on the results of a previous study. The handle is of cylindrical shape. But it is not rigidly connected to the shaft. A pitch axis between the handle and the shaft allow the user to lower his arm and keep a comfortable pose.

The purpose of the cited research studies was to have the advantages of a teleoperated robotic system in terms of dexterity in a hand-held instrument. Mechatronic hand-held devices in general are less intuitive than telerobotics system and heavier than conventional instruments, since the actuators—usually electrical motors—are mounted directly on the instrument. A novel multi-DOF hand-held mechatronic instrument is presented in this paper aiming to solve these problems.

GLOBAL STUDY OF THE INSTRUMENT USING A VR SIMULATOR

The purpose of our study was to design a dexterous instrument, with ergonomic handle, intuitive control and minimum bulk. In order to choose the optimal kinematics, and ergonomic handle and the most intuitive control mode (the way the DOF of the handle are mapped to the DOF of the end-effector), we did a global study using a virtual reality simulator. In this study, test subjects performed a series of stitching tasks to evaluate and compare different choices. In [14] the articulated handle in three different control modes and a Wii Nunchuck handle that has 2 buttons and a joystick are compared. The Nunchuck outperforms the articulated handle in all its control modes. In [15] three different kinematics for the end-effector are compared: Roll-Yaw-Roll, Roll-Yaw-Pitch and Yaw-Pitch-Roll. The results show that the the Yaw-Pitch-Roll kinematics is slightly better than Roll-Yaw-Roll and both are by far better than Roll-Yaw-Pitch in terms of time to completion of task (TCT). The Roll-Yaw-Roll kinematics is however much easier to realize in a

5 mm instrument. In the following section the mecathronic design of a prototype based on these results is explained.

PROTOTYPE DESIGN

The prototype instrument is a 5 mm instrument composed of 4 parts: an ergonomic handle, a shaft with a multi-DOF distal tip, an active trocar and a controller. Fig. 1 shows the general schema of the instrument and the real prototype. The instrument has a total of six DOF of which three DOF are manual and the other three, i.e. rotating the shaft, bending and rotating the distal tip, are robotic. To use the instrument, the active trocar is pluged on top of a normal trocar. The shaft passes through both trocars. The controller unit composed of a processor (an Arduino nano board) and power drivers is away from the instrument and communicates with the handle through an electrical cable. The actuators are powered through the active trocar.

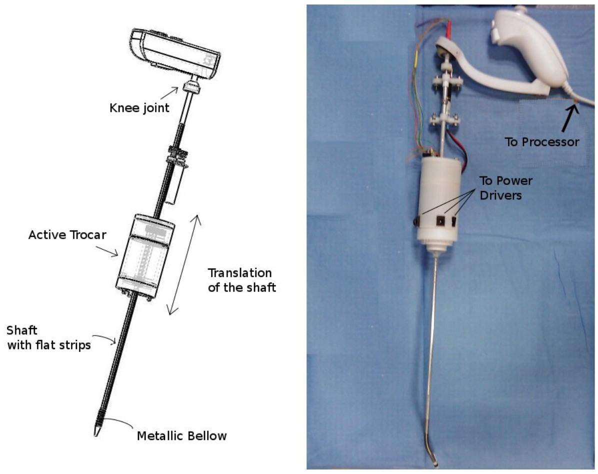

Fig. 1. The prototype instrument and its general schema

Ergonomic Handle

The handle we used for the prototype is a Wii Nunchuck controller. It is not an ideal solution for controlling the distal tip. But, it has the advantage of being ergonomically designed, so the user has a good grip on it. It is available off the shelf and has an I2C interface, 2 buttons, and a joystick. The major inconvenience of the Nunchcuk is having two commands on the joystick which can be confusing. Mostly because the movements of the joystick do not correspond to exactly similar movements on the screen. This is not the case in video games where the movements of the joystick are analogous to those of the character on the screen. The handle is connected to an Arduino Nano microcontroller board with a pulse width modulation (PWM) generator to control the actuators.

Regarding the connection between the handle and the shaft, there has been research studies on the influence of this connection on the ergonomics of the instrument and the fatigue of the user and the precision of his gestures [16], [17], [18], [19]. The results show that pistol-grip handles provide for a stable grip, but produce muscular pain due to the non-ergonomic pisition of the arm. Graspers with in-line handles are more ergonomic and need less muscular effort, when the surgeon has to approach the task sideways, but have a less stable grip and thus are less precise. One study shows that there is an optimal relative handle to shaft angle to obtain the best quality of laparoscopic bowel suturing, in terms of the accuracy of suture placement and the integrity of the suture line closure. But no significant difference in the excecution time was found between different angles [20]. The idea of changing the handle to shaft angle to improve the quality of gesture was exploited In [7]. The instrument presented has a pivot between the handle and the shaft letting the surgeon keep the handle at an angle with respect to the shaft and solve the problem of ulnar deviation and consequent pain in the arm, reported for axial cylindrical (in-line) handles.

Our solution is a spheric joint between the handle and the shaft giving the surgeon complete three dimensional freedom to position his arm. In this way, the surgeon's arm stays almost all the time near to his body with his elbow lowered and his wrist straight (see Fig. 2). This greatly reduces the stress on the arm and the postoperative fatigue. The spheric joint we used is an EGLM-16 from Igus and has a 21° pivoting angle.

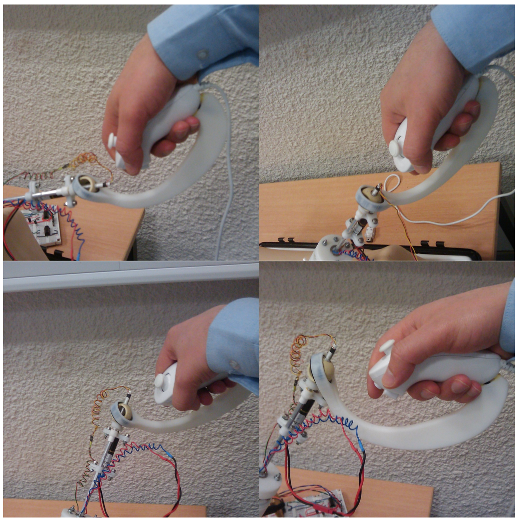

Fig. 2. The spheric joint between the handle and the shaft

Active Trocar

Our solution to make an ergonomic handle, the spheric joint between the handle and the shaft, makes it impossible to rotate the instrument's shaft manually. As a result, this rotation is motorized in our instrument by using an *active* trocar. The concept of active trocar is based on the idea of relieving the surgeon's arm and hand from supporting the wheight of the motors, encoders, gearboxes and wires as much as possible to make the instrument feel lighter and easy to use.

The active trocar holds a cylindric rotor concentric with the medical trocar and an electric motor (Maxon DC motor with a 256:1 gearhead). The rotor is coupled to the motor inside with 2:1 gears. Inside the rotor is a cylindrical canal for the passage of the shaft. The instrument's shaft and the canal have two flat strips on oposite sides so that the shaft and the rotor make a 2-DOF rotoid-prismatic joint together, i.e. The instrument can slide in the canal while the rotation of the rotor makes the shaft rotate. When the motor is activated, the shaft of the instrument rotates along with the rotor.

Except from the Nunchuck cable that goes directly to the instrument's controller unit, all the other electrical connections are on the active trocar.

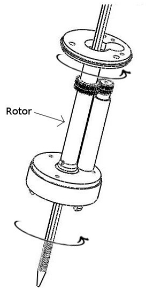

Fig. 3. The motor inside the active trocar rotates the instrument's shaft

Actuation and transmission system

At its top end, the shaft is connected to the spheric joint through a roll bearing, to compensate for the plastic spheric joint's friction. At the other end, the grasper is mounted on a metallic bellow and the bellow is fixed on the shaft. The bellow allows for transmission of rotational torques to the grasper when the distal tip is deflected and make the distal tip rotate. [15] also presents an instrument with a deflecting and rotating distal tip using a metallic bellow. In this prototype, the shaft is composed of two centered tubes. The external tube is a 4-5 mm stainless steel tube with the two opposite flat strips on it. The internal tube is 3-4 aluminiom tube through which all the wires pass. It can rotate inside the external tube, but there is enough friction between the two tubes to make the internal rotate with the external one when the active trocar rotates it. That is how the rotation of the instrument's shaft is realized.

The external tube is connected to the bellow and the grasper. The internal tube is connected to the bending structure inside the bellow. A motor (Maxon DC motor with 256:1 gearhead) is installed on top of the external tube and coupled to the internal tube through 2:1 gears. In order to make the distal tip turn around its own axis, this motor turns synchronously with the one in the active trocar. The result is that the internal tube does not rotate with the external one, conserving the orientation of the bending structure, while the distall tip and the bellow turn around their own axis.

The deflecting structure itself was borrowed from an endoscope. It is a multi-linkage sliding mecanism comprised of a cascade of pivots with parallel axes. The pivots are driven by two antagonist shape memory alloy (SMA) wires that continue all along the length of the instrument, inside the shaft. The SMA wires are pretensioned at the top of the shaft and powered through flexible wires connected on top of the active trocar. The mechatronic prototypes mentioned in the state of the art section use electric motors with encoders to control the deflection of the distal tip. Using SMA wires instead, we could remove the bulk of one motor from the instrument.

It is necessary for the instrument's user to be able to control the position and the speed of deflection of the end-effector. While speed control allows the user to go easily to the desired position, position control is essential to ensure the rigidity of the bending articulation after the desired position is reached. The control algorithm of the SMA wires (Fig. 3) switches between speed or position control depending on the control signals from the joystick. When the user is commanding the deflection, the speed control loop is active. The moment he stops, the deflection of the distal tip is measured through a shape sensor place inside the bending structure and registered as the position control loop's set point.

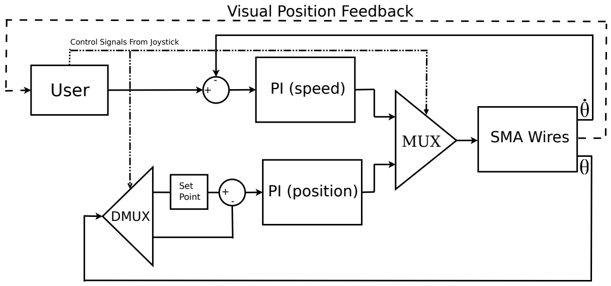

Fig. 4. The speed-position control loop for antagonist SMA wires

Control of SMA wires can be tricky considering their thermal issues, hystresis loops and slow dynamics. [21] presents a miniature articulation with antagonist SMA wires and position and force control and confirms its usefulness through experiments as the first step of the development of a robot hand. The PWM technique is used to control the position through a proportional-integral (PI) controller and the force and stiffness through a proportional controller. [22] presents the design and experimental results of controling a SMA actuator using PWM to reduce the energy consumption by the SMA actuator. A SMA wire test bed is used in this research. Open-loop testing of the SMA wire actuator is conducted to study the effect of the PWM parameters. Based on test results and parameter analysis of the pulse width (PW) modulator, a PW modulator is designed to modulate a proportional-derivative (PD) controller. Experiments demonstrate that control of the SMA actuator using PWM effectively saves actuation energy while maintaining the same control accuracy as compared to continuous PD control.

We used a PI controller with PWM technique to help prevent the wires from overheating and Eliminate the steady state error in the positio to ensure the articulation's rigidity. In order to measure the deflection of the distal tip, a shape sensor is needed. There are fiber optics miniature shape sensors that could be used to measure the deflection of the distal tip. But they are relatively expensive (1000 $) and can not be modified. The shape sensor we used is made of a carbon film on a plastic support and as a result is very low cost and it can be cut to the desired form to satisfy the application's needs in terms of size and form. But it is also prone to changes in its characteristics with temperature and deformations. So it is necessary to study the control loop carefully to see if it is reliable enough. A testbed was used to test the control algorithm and tune the PI controller before mounting the SMA wires on the instrument itself. Fig. 4. shows the diagram of the test bed. An articulating arm is attached to the shape resistive sensor to bend it as it turns around an axis. The sensor's resistance is measured in a bridge circuit and the measured signal, after being filtered and amplified, is sent to an Arduino nano board that implements the controller unit.

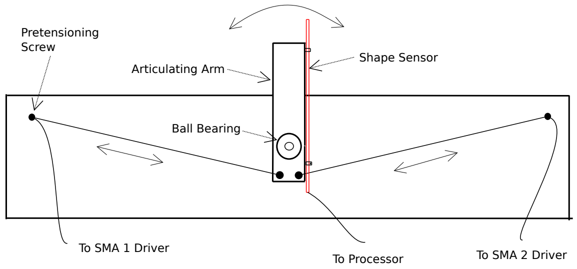

Fig. 5. The test bed used to study the closed loop control of antagonist SMA wires (Top view)

Fig. 5 shows the step response of the articulation for 10% increases in position set point and external dynamic load.

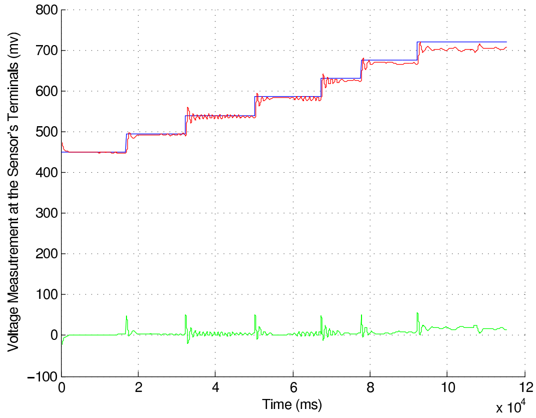

Fig. 6. The step response of an articulation with two antagonist SMA wires and PWM position controller on a test bed

The steady state error in position is near zero which ensures rigidity except for the end that corresponds to a 75° deflection. Indeed, the structure of the test bed does not allow the articulating arm to bend more than 70° approximately. The tuning process needs to be repeated on the actual prototype for two reasons:

1) the thermal conditions that affect the dynamics of the SMA wires are different;
2) the sensor's shape, dimensions and placement are different in the prototype than in the test bed.

A miniature automatic grasper for such an instrument needs to provide the grasping forces needed in surgery. These forces are estimated to be between 30 N and 50 N for holding a needle when suturing [23]. In [24] a grasper actuated by a miniature DC motor and SMA wires is presented. A major problem of this grasper is its length (4.5 cm) that causes extra forces on the bending structure of the distal tip. We made a simple hydraulic grasper that is closed by filling a balloon placed under the near end of its jaws with water. The balloon is filled through a canal that runs along the wires inside the shaft and is connected to a syringe. Fig. 8 shows the grasper closed.

EXPERIMENTAL RESULTS

In order to validate the proof of concept prototype, we did some in vitro and then in vivo experiments. In vitro tests were to see if a naive user could combine the manual and robotic movements of the distal tip to make a desired gesture such as picking a needle and turning it to make a stitch. This was done successfully.

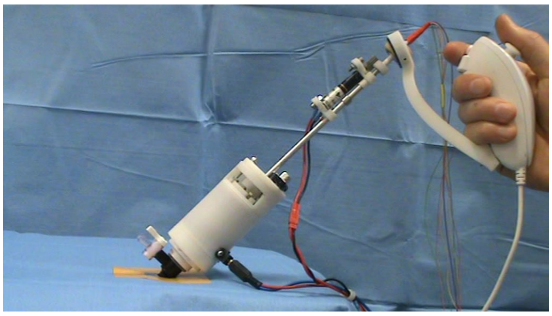

Fig. 7. In vitro set up

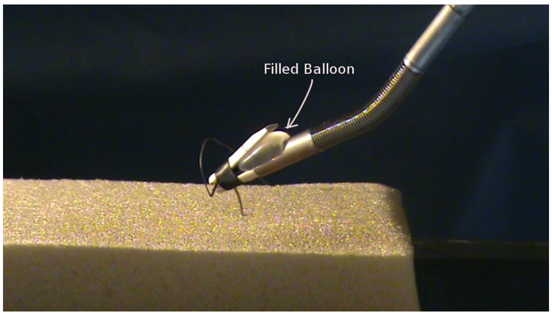

Fig. 8. Pincer holding a needle

An in vivo on a porcine model ensued to have the instrument tested by an expert surgeon. The surgeon was able to coordinate easily the distal tip movements with the endoscopic vision, grasp a needle and make a stitch in soft tissue.

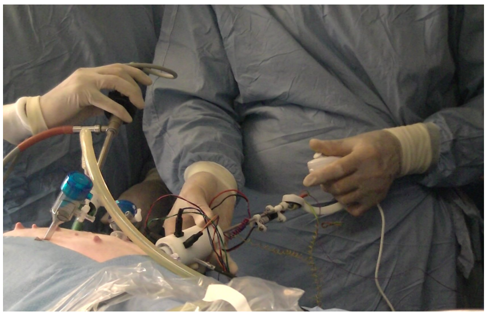

Fig. 9. In vivo set up

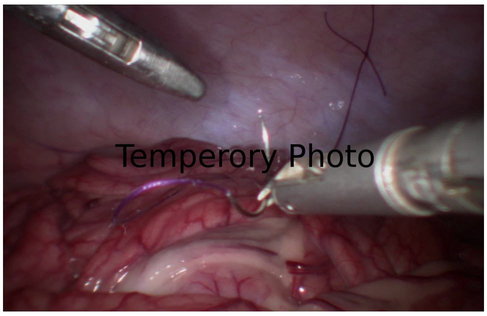

Fig. 10. Pincer holding a needle

CONCLUSION

The problem of making a dexterous, intuitive and ergonomic instrument for laparoscopy is the focus of our research. Making such an instrument needs a global study of these problems. The research conducted in this directions has provided some solutions, but technological realization of these solutions has not resulted in a satisfactory outcome yet. We developed the concepts of active trocar and free-orientation-handle as answers to some of the shortcomings of the previous efforts.

The prototype instrument developed based on these concepts was tested in vitro and in vivo to make surgical gestures. The new handle helps reduce the burdeon on the surgeon's arm, while the active trocar simplifies the mechanical transmission system and maintains the rigidity of the end-effector. The hydraulic grasper proves to be an effective solution to the problem of designing an automatic miniature grasper.

To make the future instrument more intuitive and shorten its learning curve, the design of the handle, its controlling elements and how each of them is coupled to the distal tip's DOF must be studied in .

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